MICROCOPY RESOLUTION TEST CHART

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RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

RUBBER TO BACKING BOND STRENGTH
FOR STAVE BEARINGS

by

Thomas L. Daugherty

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APR 27 1984

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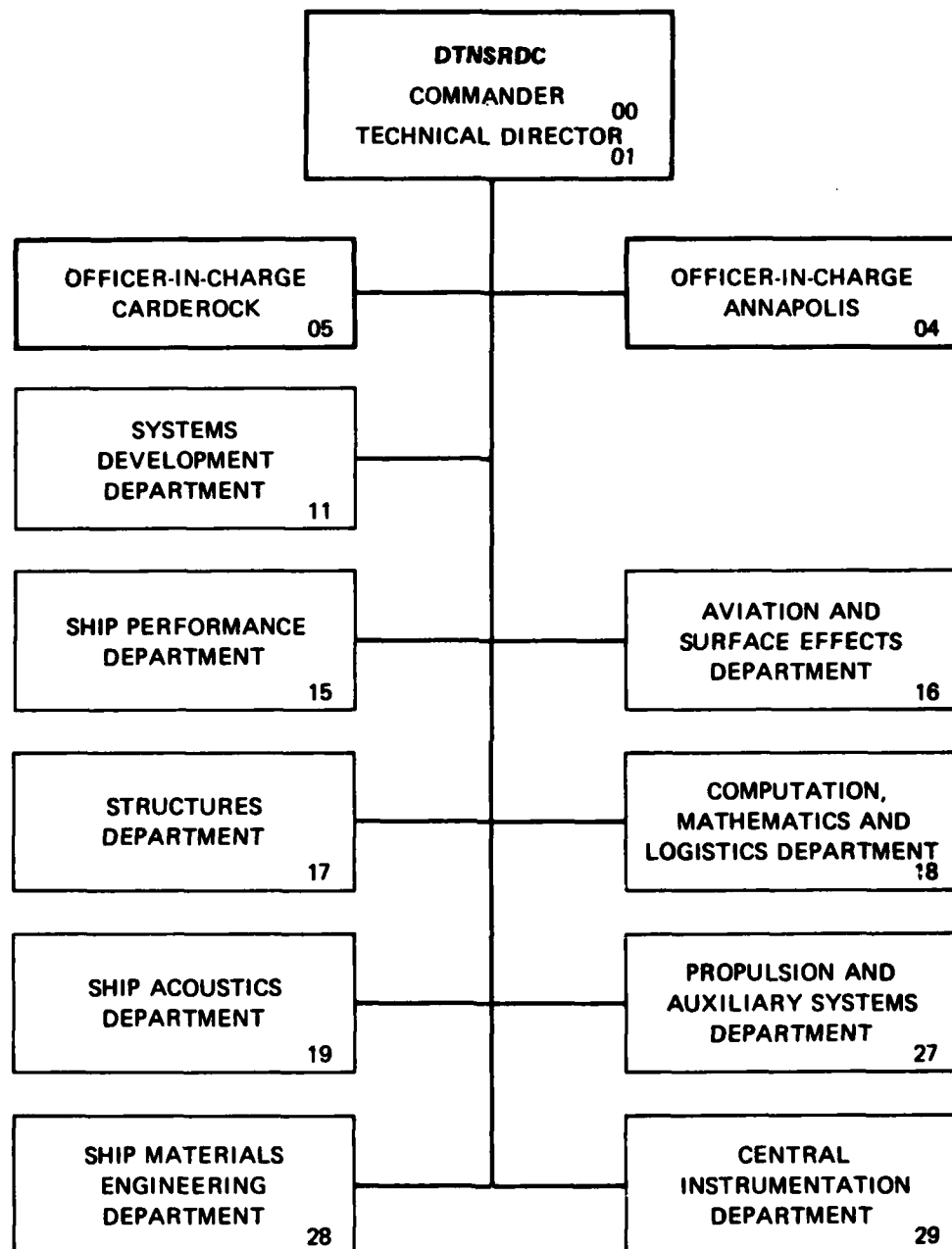RESEARCH AND DEVELOPMENT REPORT

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Rubber-surfaced stave bearings in most U.S. Navy ships support the propulsion shafting and propeller aft of the main shaft seal. Problems have been encountered with inadequate bonding of the rubber surface to their brass backing and with corrosion of the brass backing. The objective of this work was twofold: to develop improved specification criteria that would ensure reliable bonding between the rubber surface and the backing, and to evaluate the bond
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strength of alternative backing materials that eliminate corrosion.

Right angle adhesion bond tests were used as a measure of the strength of the bond between the rubber surface and the backing of six conventional bearing staves and three special designs. Specimens from each group were examined in the as-received condition and after treatment by: immersion in seawater for 3, 6, and 12 months; exposure to thermal cycling for 45 and 90 days; immersion in oil for 46 hr and 3 months; and heating at $158^{\circ}F$ in an oven for 96 and 240 hours.

No problems were encountered using 1/2-in.-wide strips of the rubber surface instead of the previously required 1-in. strips for the right angle pull tests. The 1/2-in. size permits evaluation of bonds along the edges as well as in the center of the stave. The mean baseline bond strength between the rubber and the backing and/or the tear strength of the rubber varied by as much as a factor of two among the nine groups tested. Most staves met the existing specification criteria of MIL-B-17901 for unaged and aged conditions. New specification limits are recommended based upon the behavior of the conventional brass-backed staves when exposed to the environmental tests. Baseline bond and/or tear strength of the plastic- and hard rubber-backed staves ranked second the third best respectively in the unaged condition. However, the measured bond and/or tear strength of the plastic-backed stave deteriorated after exposure to seawater, thermal cycling, and oil immersion. The results probably reflect properties of the rubber used because most specimens of the plastic-backed design failed by tearing within the rubber rather than by adhesion at the interface. The rubber surface is softer than that specified for the Class I stave bearing. Despite the strength reductions observed after being subjected to the environmental conditions, the plastic-backed staves met the present specification limits. Both hard rubber and plastic appear to be adequate materials to meet the adhesive bond strength requirements of the specification.

Recommended changes to the military specification with rationale for each change are proffered for both brass-backed and nonmetal-backed bearing staves. Many of these changes have been incorporated into a specification revision (MIL-B-17901B of 17 June 1983).

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ADMINISTRATIVE INFORMATION

This study of the adhesion strength between the rubber and backing surfaces of stave bearings was conducted with O&MN funds provided under Naval Sea Systems Command Project Order N00024-81-PO-01132, Work Unit 2832-500. Funds to document findings were provided under Work Request N0002483WR20243, Work Unit 2832-624.

INTRODUCTION

Rubber-surfaced stave bearings in most U.S. Navy ships support the propulsion shafting and propeller aft of the main shaft seal. They are called sterntube and strut-bearings. The seawater in which the bearings are immersed acts as a lubricant and coolant. Stave bearings are made in accordance with Military Specification MIL-B-17901[1]* (Class I) and a Naval Ship Systems Command Standard drawing.[2] Each stave consists of a layer of synthetic rubber bonded to a naval brass backing. A typical sterntube or strut bearing (see Figure 1) is made up of approximately 16 separate staves, spaced evenly about the circumference of the bearing housing. Each stave is installed in a dovetail slot in the housing. Space between adjacent staves permits water flow. The bearings normally are sized to carry a load of about 40 lb/in.[2] (based upon projected area.)

There was a rash of stave-bond failures in the mid-1970's. Most of the failures occurred on staves manufactured by one company. It appeared that the rubber separated from its metal backing at the edges of the stave and progressed toward the center. The problem usually was detected before complete separation.

This bonding problem raised questions concerning the cause of the failures and why the problem was not detected during the normal inspection testing for quality conformance. Although the manufacturer claimed that the bond deteriorated because of corrosion (dezincification) of the naval brass backing, his argument could not be supported by the condition of the defective staves. Poor quality control by the manufacturer could be one explanation for the problems.
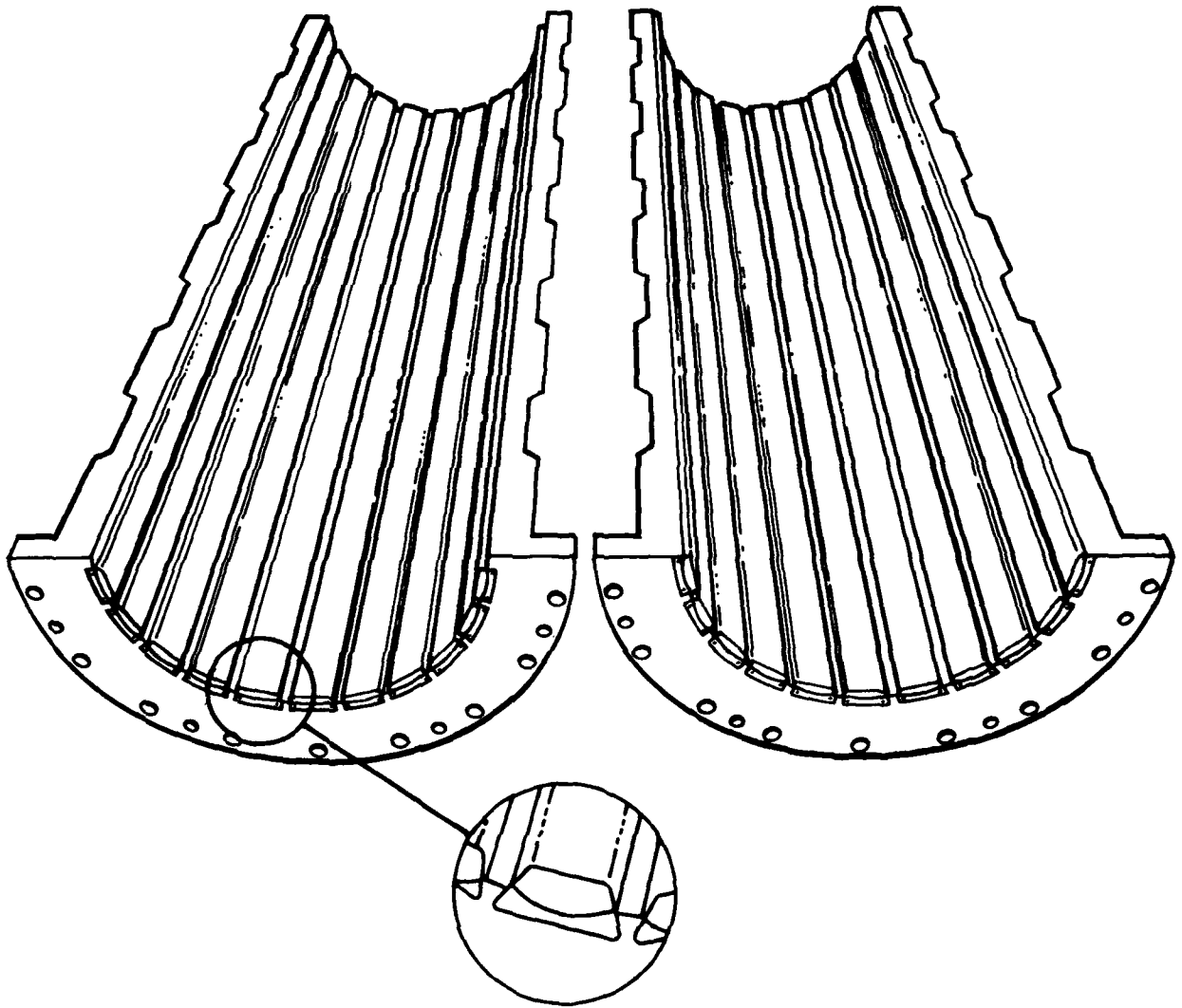
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*A complete list of references is given on page 45.

Figure 1 - Typical Stave Bearing Construction

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Specification MIL-B-17901A requires that a sample selected at random from every lot of bearings purchased by the government be tested for quality conformance. Inspection consists solely of examining each sample bearing to determine "conformance with the specification requirements not involving tests."[1] The inspection procedure does not provide a technique to examine the bond, even qualitatively. Furthermore, it is doubtful that bond problems along the edges of the stave would have been detected even under the qualification test section of the specification that was in effect in the mid-70's, because the tests did not require a detailed examination of the edge bonding. Adhesion bond tests on 1-in.-wide strips from only the center of the staves were specified.

The adhesion tests required by the qualification portion of the specification at the time that the bond problems occurred are summarized below.

- Select sample staves at random from each bearing lot. The quantity selected is a fraction of the lot size and is specified in tables.
- Cut two 6-in.-long specimens from each sample stave.
- Make two parallel longitudinal cuts, 1 in. apart, in the central portion of the synthetic rubber face material.
- Cut or buff the synthetic rubber face to a 1/4-in. thickness.
- Remove excess rubber on the edges of the bearing, carefully leaving a 1-in.-wide rubber strip approximately in the center of the bearing strip.

The specimens then are subjected to right angle pull tests in the following conditions: unaged, oven aged, and immersed in oil. Two specimens are tested for each condition and the value for adhesion is determined as the average force required to separate the rubber from the backing material of each specimen. Each rubber test strip is cut at one end along the interface between rubber and backing enough (about 1 in.) so that the end could be clamped in a grip. The metal base of the specimen is placed in a special holding device that mechanically maintains a pulling motion at right angles to the base. After the test strip is clamped in the gripping device, it is pulled at right angles to the base at a rate of 2 in./min. The force required to maintain this head speed is recorded on an autographic chart. The force is ignored during initial load build-up, when the rubber is elongated without being stripped from the backing material. If the rubber begins to tear within the rubber rather than separate at the interface (bond)

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of the rubber and backing, the strip is cut with a sharp knife at the interface (to encourage bond failure) and the test continued. If the strip persists in tearing in the rubber instead of separating at the bond, the average load at which tearing occurs is reported, and the type of failure noted.

Amendment 4 was issued (Nov 1978) following the bond problems experienced in the mid-70's and changed the qualification test portion by adding adhesion bond tests after seawater immersion and after thermal cycling. The seawater immersion tests used 1/2-in.-wide strips along each edge of the bearing and one from the center. The minimum bond strengths specified after seawater immersion and thermal cycling were based on engineering judgement.

Most of the test procedures and adhesion bond strength requirements contained in MIL-B-17901 were based largely upon the experience of the stave manufacturers. Very little documentation exists on the effect of environmental factors on the adhesive bond between the rubber surface and the naval brass backings. The principal environmental factors of interest are aging at elevated temperature, oil immersion, seawater immersion, and thermal cycling.

Recently, the U.S. Navy has been evaluating nonmetal-backed stave bearings to eliminate the corrosion problems of the naval brass backing because naval brass frequently deteriorates due to dezincification, and the staves loosen and become noise sources. The Navy has been evaluating two nonmetal-backed stave designs—a plastic backing and a hard rubber backing. Both types appear to bond well to the nitrile rubber usually used for stave bearings. There are only limited data on the behavior of the bond between these backings and their mating surfaces under the environmental conditions discussed above.

For these reasons, the principal objectives of this study were:

1. To develop improved specification criteria that will ensure reliable bonding between the rubber surface and the backing.

2. To evaluate the bond strength of alternative backing materials that eliminate corrosion.

TEST PROCEDURE

Bearing staves were obtained from each of the four manufacturers listed on the qualified products list for Class I stave bearings, under MIL-B-17901. Staves were ordered from Federal stock and directly from the manufacturer. Three special

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bearing stave designs representing other backing materials or designs also were obtained--a plastic backing, a hard rubber backing, and a swing-pad design. All three designs have been undergoing shipboard evaluation and are of significant interest to the Navy.

Adhesion tests were conducted using the right-angle pull test method specified in MIL-B-17901 (reference 1) and discussed briefly in the "Introduction" section. The specimen strips were 1/2-in. instead of 1-in. wide. The objective of the adhesion test is to quantify the bond strength between the rubber surface and the backing material. It is recognized that in a number of cases the bond strength may exceed the tear strength of the rubber. Then, the adhesion strength cannot be quantified. One can only conclude that the adhesive strength exceeds the value recorded for the rubber tear. Also, a tear failure in the rubber is as undesirable as a bond failure. Therefore, the rubber tear strength is used as a rejection criterion if it falls below an acceptable limit.

PRELIMINARY TEST

Right-angle adhesion bond tests were conducted on two samples using 1/2- and 1-in. wide adjacent test strips on each sample. The purpose was to determine the feasibility of using a 1/2-in. test strip in our tests. The samples were selected to represent the two expected failure modes, bond failure and tearing within the rubber. We expected that these two samples would reveal any major, unexpected problems (for example crosswise tearing) that might result from the use of narrower test strips. These two samples were not tested further.

PREPARATION FOR BASELINE AND ENVIRONMENTAL TESTS

The staves were divided into groups by manufacturer and source (Table 1). Ten 7-in.-long specimens were cut from each group. Set 10 was kept as a spare in case problems developed in the other sets. (None did, so set 10 remained a spare throughout the tests.) The rubber surface of each specimen was machined to a nominal 1/4-in. thickness.

Six 1/2-in.-wide adhesion test strips were prepared by cutting right angles longitudinally through the rubber surface every 1/2 in. (Figure 2). The strips were numbered 1 to 6 on each specimen. The swing-pad stave was a No. 8 cross-section size stave and was not wide enough for six strips. Consequently, only five 1/2-in.-wide test strips were prepared for the swing-pad design.

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TABLE 1 - STAVE GROUP IDENTIFICATION

Group I.D.	Manufacturer	Cross-Section Size	Source of Supply	Design
I	A	No. 9	Federal Stock	Conventional
II	A	No. 10	Manufacturer	Conventional
III	B	No. 10	Federal Stock	Conventional
IV	B	No. 10	Manufacturer	Conventional
V	C	No. 10	Federal Stock	Conventional
VI	D	No. 10	Manufacturer	Conventional
VII	E	No. 10	Manufacturer	Plastic-Backed
VIII	F	No. 10	Manufacturer	Rubber-Backed
IX	G	No. 8	Manufacturer	Swing-Pad

BASELINE ADHESION TESTS

Baseline adhesion tests were conducted on test strips 1, 3, and 5 for all ten specimens from each of the nine groups. Strip 1 was along an edge; strips 3 and 5 were near the center of the width of the bearing stave. The width of each strip was measured with a dial indicating caliper and recorded so that the strength could be compared on the basis of 1/2 in. The procedure used to conduct the pull test was the same as that in the qualification portion of the specification at the time of the bond problems. It was described above. The force required to pull each test strip from the specimens was recorded on the autographic recorder. The force gage was calibrated each day before the pull tests. A note was made to indicate the mode of failure when the rubber tore.

ENVIRONMENTAL TREATMENTS

Nine sets of bearings, each containing one 7-in. specimen from each of the groups I through IX (identified in Table 1), were numbered for identification and subjected to the following conditions:

> Set 1 - Immersed for 3 months in flowing seawater circulated at about 20 in/sec.

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Set 2 - Immersed for 6 months in flowing seawater circulated at about 20 in./sec.

Set 3 - Immersed for 12 months in flowing seawater circulated at about 20 in./sec.

Set 4 - Thermally cycled for 45 days. The staves in this set were placed in a refrigerator controlled at 32° to 40°F for a continuous 8-hr period. They were then removed to a temperature of 72° to 80°F for 16 hr and the cycle repeated. Cycling was conducted on work days only for 45 total calendar days. The staves were kept at 72° to 80°F on weekends and holidays. This plan resulted in 30 thermal cycles.

Set 5 - Thermally cycled as set 4 above for 90 days. There were 60 cycles.

Set 6 - Immersed in a petroleum-based oil at 77° to 87°F for 46 hr. The oil was ASTM oil No. 3 having a viscosity of 155 ± 5 Saybolt Universal Seconds at 100°F, an aniline point of 157.1° ± 1.8°F, and a flash point of 330° ± 5°F.

Set 7 - Immersed in the same oil at the same temperature as set 6 above but for 3 months.

Set 8 - Oven aged in air at 158° ± 2°F for 96 continuous hr.

Set 9 - Oven aged under the same conditions as set 8 above but for 240 hr.

The seawater exposure tests of sets 1, 2, and 3 were conducted in Wrightsville Beach, NC under contract with LaQue Center for Corrosion Technology, Inc., a unit of INCO Corporated. The stave specimens were attached to a plexiglass support rack as shown in Figure 3, with the rubber facing upward and parallel to the seawater flow. All other exposures and tests were conducted at the Center.

After each set of specimens was exposed to the conditions described above, the remaining three strips of rubber on each specimen were pull-tested in the same manner as before.

DESCRIPTION OF TEST STAVES

Group I through VI of Table 1 were made up of conventionally designed staves that should conform to both MIL-B-17901A[1] (Class 1) and the Naval Ship Systems standard drawing.[2] Each stave was made of synthetic rubber with a hardness range of 85 ± 5 Shore A units, instantaneous. The backing material was naval brass. The thickness of the rubber surface in the conventionally designed staves varies considerably across the width due to the shape of backing. Figure 2 shows the shape of the stave before and after preparation for adhesion pull tests. The longitudinal

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CONVENTIONAL STAVE BEFORE
PREPARATION

CONVENTIONAL STAVE AFTER
MACHINING OF SURFACE TO 1/4-in.
THICKNESS AND MAKING OF
LONGITUDINAL CUTS

NONMETALLIC STAVE AFTER
MACHINING OF SURFACE TO 1/4-in.
THICKNESS AND MAKING OF
LONGITUDINAL CUTS

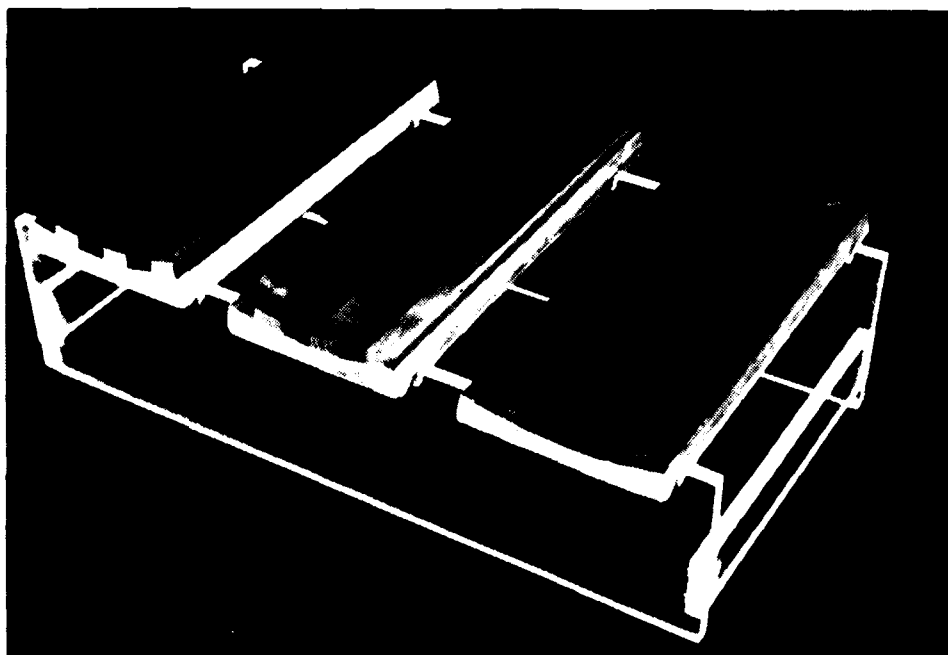Figure 2 – Preparation of Test Specimens

Figure 3 - Mounting of Stave Specimens for Seawater
Immersion Tests

cuts in the 1/4-in.-thick rubber were made at right angles to the rubber surface after the surface had been machined to the 1/4-in. thickness required.

Group VII consisted of staves having a synthetic rubber surface of uniform thickness bonded to an ultra high molecular weight polyethylene plastic backing (Figure 4). The rubber had a hardness of 70 $\pm$ 5 Shore A units, instantaneous.

Group VIII staves were made of a synthetic rubber surface of uniform thickness bonded to a hard rubber backing (Figure 4). The surface rubber hardness was 85 $\pm$ 5 Shore A, instantaneous. The backing hardness was about 87 Shore D.

Group IX was composed of swing-pad staves (Figure 4). This design is a uniformly thick surface of synthetic rubber bonded to a naval brass support base. The base is bonded to a series of rubber and brass laminates and to a naval brass backing. The hardness of the surface rubber and the laminates was 85 $\pm$ 5 and 55 $\pm$ 5 Shore A durometer, instantaneous, respectively.

The stave bearing faces of the first eight groups had flat surfaces; Group IX, the swing-pad design, had a curved surface with a radius slightly larger than the shaft radius.

ADHESION BOND TEST MACHINE

The machine used to conduct all the adhesion bond tests is shown in Figures 5 and 6. It contains the following components.

Grips clamp the end of the rubber test strip.

Head provides controlled rate of movement used to remove rubber strips. (For the tests described here the speed was set at 2 in/min.)

Load Cell indicates force required to maintain head speed while causing separation of stave bond or possible rubber tear. Output attached to autographic recorder. Daily calibration check with 25-lb dead weight.

Fixture holds base of stave to ensure desired 90° angle to backing surface in width direction. Base is tilted to obtain correct angle (Figure 6).

Carrier provides 90° pull angle as the strip is removed. Unit is mechanically controlled; the carrier crank is used by the machine operator to adjust the angle as the strip is removed (Figure 6).

Autographic chart prints out continuous trace of the magnitude of force needed (as sensed by the load cell) to pull the test strip from the backing.

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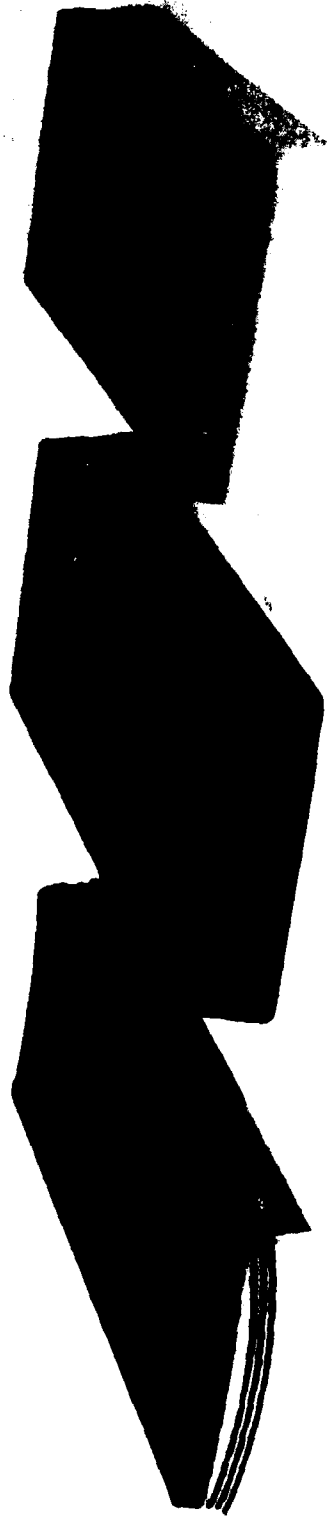
(a)   (b)   (c)

Figure 4 - Special Stave Designs Before Modification: (a) Swing-Pad, (b) Rubber Backed, and (c) Plastic Backed

Figure 5 - Right Angle Pull Test Machine
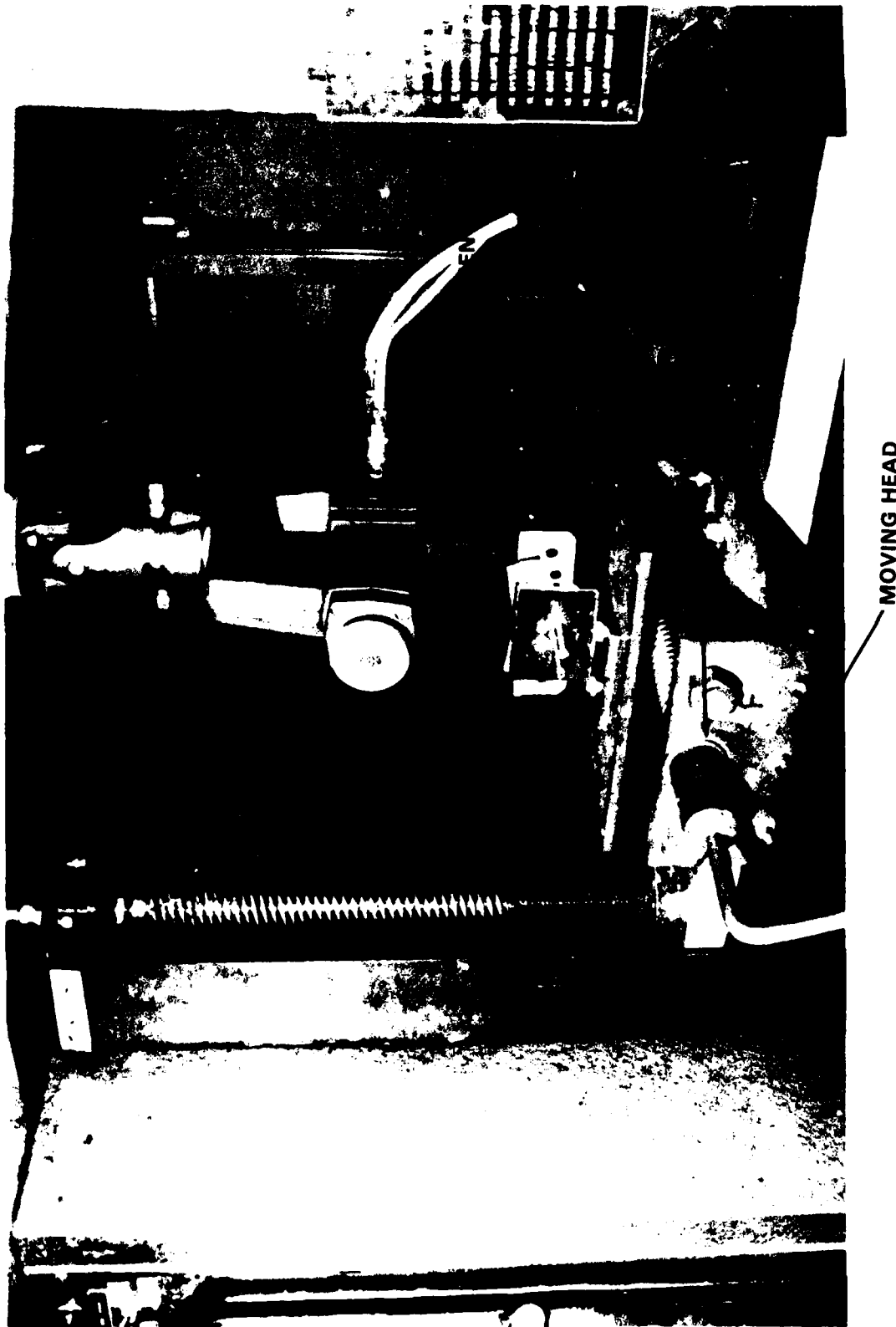
MOVING HEAD

Figure 6 – Adhesion Test Machine Showing Grips, Fixture, Carrier, Moving Head, and Stave Test Specimen

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The following steps were taken to reduce the experimental error in the adhesion pull tests:

- The same machine was used for the entire test.
- The same test mechanic conducted all tests.
- The load cell was calibrated just before each use, and
- The same procedure was followed for all tests.

CRITERIA FOR SPECIMEN FAILURE

The mode of failure of the test strips subjected to right angle pull tests was identified in accordance with MIL-B-17901, viz., adhesive or tear failure. In staves bonded with a cement, an adhesive failure is considered as one of the following:

1. Failure at the rubber interface with the cement.
2. Failure within the cement layer.
3. Failure at the cement interface with the backing.
4. A combination of the above.

A tear failure occurs in the rubber away from the bond line. The strength of the adhesive bond itself is therefore not measured. When rubber tears, the operator cuts the rubber back to the rubber-backing interface in an attempt to cause separation at the bond. The adhesion bond strength is presumed to exceed the recorded tear strength when the rubber tears during the right-angle bond test. Note that failure can occur due to a combination of adhesive and tearing modes on the same test strip or within the same specimen.

Figure 7 shows the condition of the stave rubber and backing surfaces after separation by adhesive and tear modes. Figures 8 and 9 show typical autographic chart records for the two failure modes. The force used to compare bond strengths for separation of the rubber and backing is determined by inspecting the autographic chart. The level of force required to remove the test strip is generally very consistent when the bond failed through adhesive mode. A line representing an average pull force required usually can be drawn through the autographic chart so that the variation above and below that line is the same. However, the level used to determine failure by rubber tear is not consistent. First, the force decreases suddenly as the interface is cut; then the force builds up quickly until rubber tears and the process is repeated. A line is drawn through the peaks in the augographic chart to a point where the force begins to level off.

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(a)   (b)
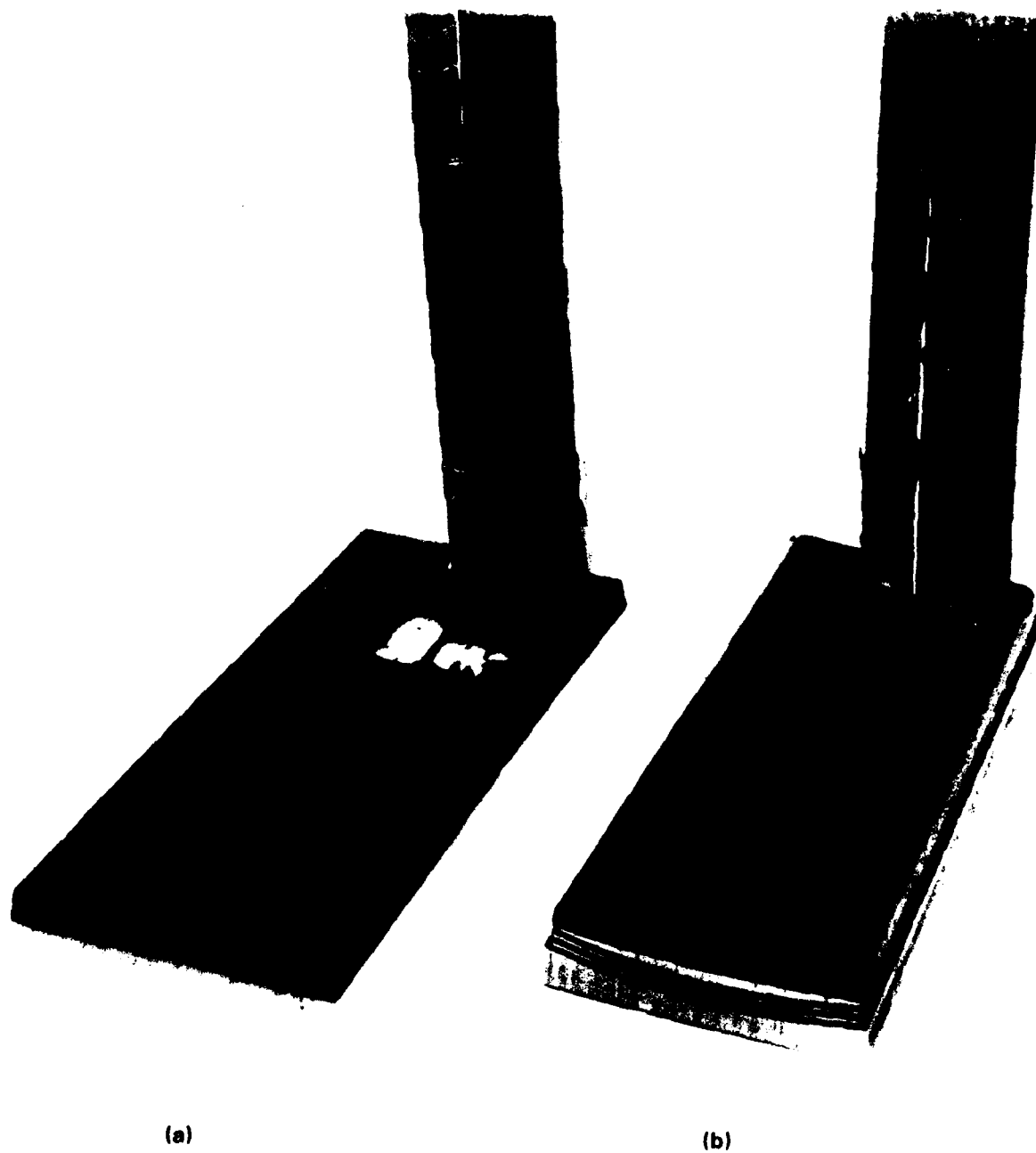
Figure 7 - Condition of Surfaces After Pull Tests in Which Samples
Failed by (a) Tear and (b) Adhesion Mode
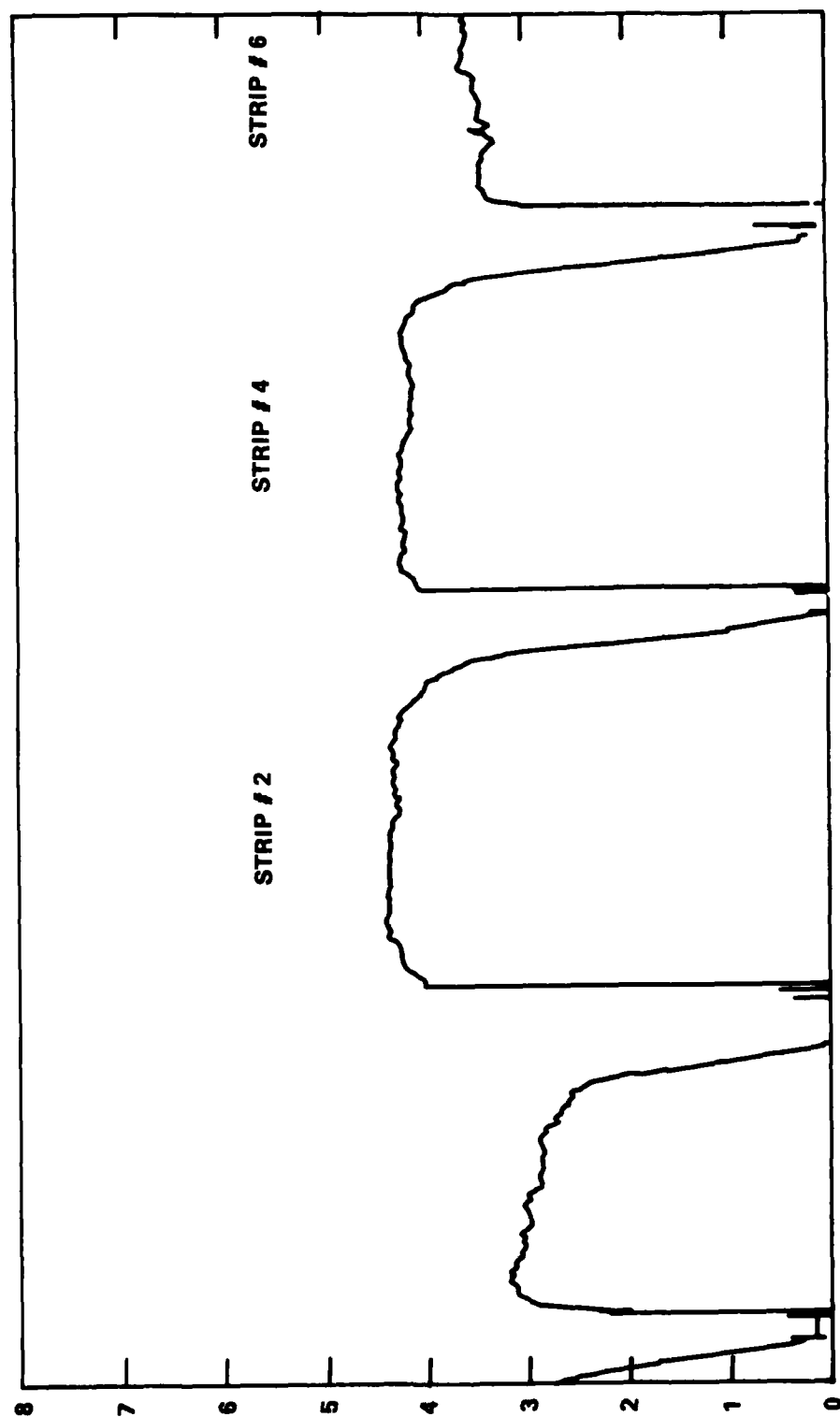
Figure 8 - Autographic Chart for Adhesion Failure Showing Magnitude of Force Versus Time

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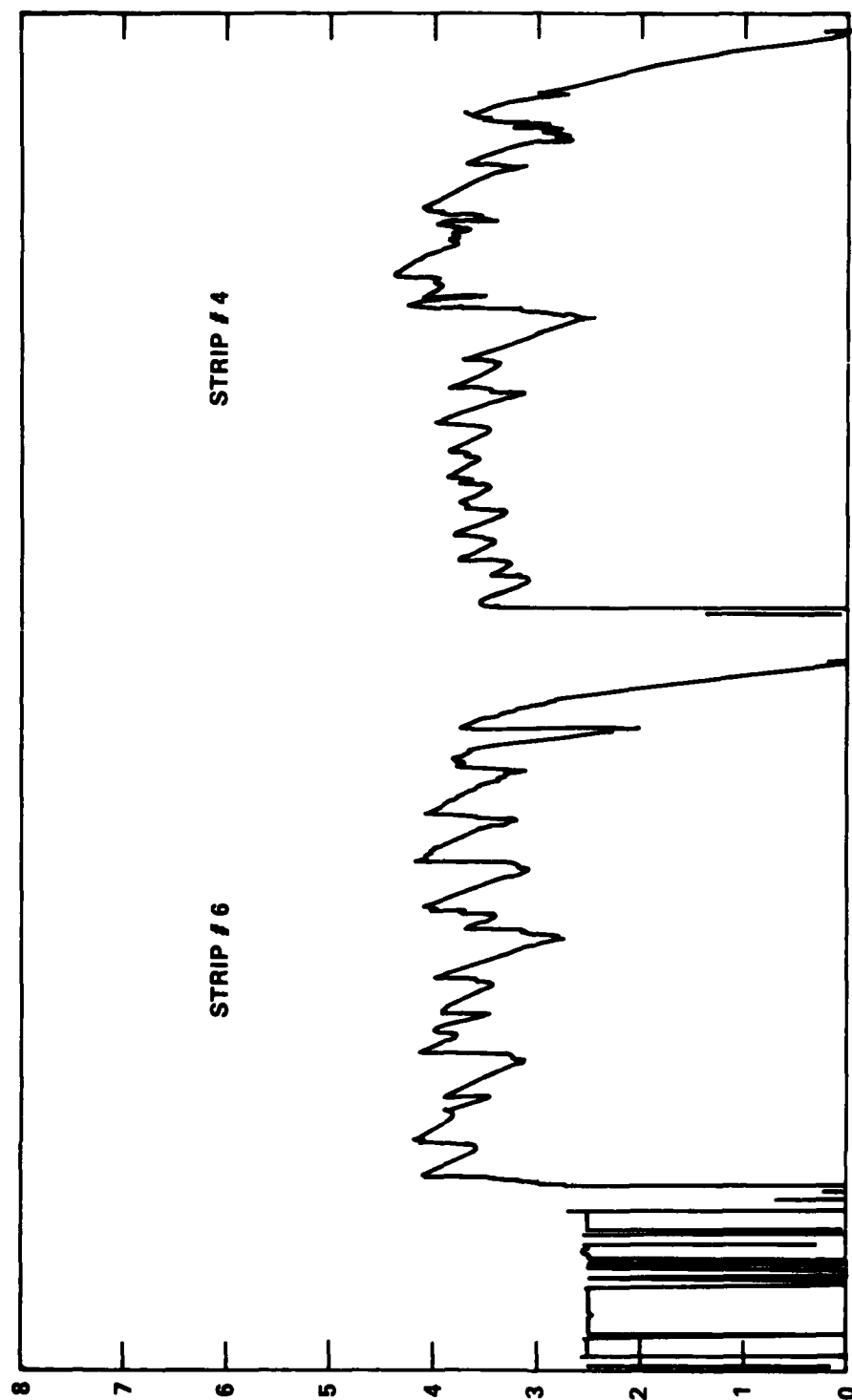
Figure 9 – Autographic Chart for Tear Type Failure Showing Magnitude of
Force Versus Time

RESULTS AND DISCUSSION

PRELIMINARY TEST

All adhesive test strips were nominally 1/2-in. wide unless otherwise stated. All adhesive bond tests specified in MIL-B-17901 for Class I, stave type bearings, use 1-in. widths except the seawater immersion test of Amendment 4, which uses a 1/2-in. width. A preliminary test comparing adjacent 1/2- and 1-in. strips was conducted to check whether adhesive strength based upon 1- and 1/2-in. widths may be compared by multiplying the force value for the 1/2-in. strips by two.

Based upon previous experience with these staves, one piece was selected from Group VII and one from Group IX to represent the rubber tear and the adhesive type failure modes, respectively. Adjacent test strips of 1/2 and 1 in. from the central region of both specimens (see Figure 10) were pulled at 90° in the manner described previously. It was frequently necessary to cut the rubber of the Group VII specimen at the bond because the rubber tore often. The force required to pull the 1/2-in. strip was 54 lb, versus 98 lb required to pull the 1-in. strip. The specimen from Group IX failed by adhesive mode; the forces required to separate the 1/2- and 1-in. strips were 25 and 50 lb, respectively.

BASELINE ADHESION TESTS

The bond tests on strips 1, 3, and 5 from the ten specimens from each of the nine stave groups provided the baseline data before the staves were subjected to the environmental tests. Strip 1 was along one edge of the stave, and the other two strips were closer to the center (widthwise). Table 2 lists the mean ($\overline{X}$) and the standard deviation (s) of the force required to separate the test strip from the stave backing in each group, the relative ranking of the means, and the mode of failure. The mean, $\overline{X}$, and standard deviation, s, were calculated from the usual formulas:

$$\overline{X} = \frac{\sum_{i=1}^{i=n} X_i}{n}$$

where X_i = the force required to separate the rubber surface from the backing for the ith specimen

and n = total number of specimens.

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Figure 10 - Test Strips 1/2- and 1-in. Wide on Specimens Exhibiting Tear Type and Adhesive Type Failure

$$s = \sqrt{\frac{\Sigma X_i^2 - (\Sigma X_i)^2/n}{n-1}}$$

TABLE 2 - FORCE REQUIRED TO SEPARATE TEST STRIP FROM
STAVE BACKING IN BASELINE ADHESION BOND TESTS

Stave Group	$\overline{X}$ Group Mean* of Force at Failure (lb)	s Standard Deviation, (lb)	Dominant Mode of Failure**	Ranking of Group Means
I	39.0	8.0	A	4
II	30.4	3.5	T&A	7
III	28.2	3.6	A	8
IV	33.0	4.9	T&A	5
V	35.4	7.6	T&A	5
VI	54.6	5.5	A	1
VII	46.2	8.1	T	2
VIII	42.1	3.7	T	3
IX	26.9	7.2	A	8

*Means calculated using adhesion test results on Sets
1 through 10, Strips 1, 3, and 5. Values corrected to
nominal 1/2-in. strip width; for comparison with results
of tests on 1-in. strips, multiply by 2.
**A is failure at adhesion bond; T is failure by
tearing of rubber. T&A means that failure occurred by both
tearing and adhesive modes.

A t-test was used to determine difference between the means of the nine groups
at 95% level. Appendix A contains a sample calculation. All group means were sig-
nificantly different from each other except those of Groups III and IX, and Groups
IV and V.

Tables 3 through 11 list the forces required to cause failure of the individual
strips in each group before they were exposed to the environmental tests. The bond
or tear* strength along the edges of these samples was compared to the strength in

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*The term bond or tear used throughout this report is used to define three
modes of failure: adhesion bond failure, tearing of the rubber, and a combination
of an adhesive bond and rubber tear failure.

the other two strips from the central region of the specimen for each group. A t-test was applied at the 95% confidence level. Appendix B presents a sample calculation. Only for Groups I and VIII was tear or the adhesion bond strength at the edges significantly different from that at the center. The bond or tear strength along the edge in Group I was significantly less than that of the central strips, whereas for Group VIII the strength along the edge was greater than that in the central strips.

Staves from Groups I and II were manufactured by Company A. Groups III and IV were manufactured by Company B. The mean bond or tear strengths for staves from the same manufacturer are significantly different, indicating that a variation in strength would be expected from lot to lot in staves from the same manufacturer. In addition, the standard deviation, which is a measure of the variation of the data about the mean, also varied widely in staves from Company A. Some of these differences may have been caused by exposure of the staves to various environmental conditions after fabrication and before the beginning of these tests. Groups II, IV, VI, VII, and VIII were obtained from the manufacturer directly and therefore were presumably fabricated in 1978, when the materials were ordered for the test. Group I, III, V, and IX were made in 1976, 1973, 1967, and 1975, respectively. Some of the differences in bond strengths observed among the unaged staves from a particular manufacturer are attributable to these various lengths of storage time and to exposure to unknown conditions since manufacture. The rest of the differences result from process and random variability.

The baseline adhesion tests for brass-backed conventional staves, Groups I through VI, can be compared with the specification criteria for the unaged adhesion test, which requires a minimum adhesion bond strength of 40 lb, based upon a 1-in. test strip.[1] Table 2 shows that the mean bond or tear strength of all six groups exceeded the specification limit. (All bond or tear strength values in the tables must be multiplied by two for compatability with the specification limit because the test strips were 1/2 rather than 1-in. wide.) All but one of the individual readings for unaged test strips in Groups I through VI, which are shown in Tables 3 through 11, also exceeded the minimum value in the specification.

Bond strength of specimens in the as-received condition from Group VII (plastic-backed) and VIII (rubber-backed) greatly exceeded specification values. The mean bond or tear strength for Groups VII and VIII ranked second and third highest, respectively, in a comparison of all nine groups. The dominant failure mode for both groups was by rubber tear. The mean strength for Group IX (swing-pad design) was the lowest of all groups. Five strips of the 26 tested for Group IX in the as-received condition failed to meet the 40 lb/in. specification requirement. Failure of Group IX was by adhesive mode.

The failure rate for the populations of the six groups of brass-backed conventional staves may be estimated in the following manner. Assuming a normal distribution for bond failures, 95% of the data should fall within the limits of X-2s and X+2s. A one-tailed test is used because the specification requires only a minimum value. For a one-tailed test, 97.5% of the data would be expected to fall above the value of X-2s. The value of X-2s, based upon 1-in.-wide strips, is 46, 46.8, 42, 46.4, 40.4, and 87.2 lb for Groups I through VI, respectively. Thus, slightly less than 2.5% of the population from Groups I through V would be expected to fail the existing unaged specification limit of 40 lb/in. Even fewer from Group VI would be expected to fail. Similarly, the expected failures of Groups VII and VIII using the 40 lb/in. of width specification limit would be much less than 2.5%.

The failure rate for Group IX, however, would be much larger than 2.5%. The failure rate of group IX population is approximately that associated with applying one standard deviation to the mean. For a one-tailed test the rejection rate associated with one standard deviation is 16%. This is close to five of the 26 strips (19% failure) tested which we observed.

ENVIRONMENTAL TREATMENT

Life Cycle of Bearing Staves as Related to Environmental Treatment

The real bond strength between the rubber surface and its backing that is required to ensure reliable operation is unknown. It is useful to examine the life cycle of bearing staves and discuss the rationale behind the adhesive bond tests contained in MIL-B-17901. Manufacturers must meet qualification test requirements to be eligible to provide bearings to the government. A sample from each lot ordered from a previously qualified manufacturer must be subjected to quality conformance inspection tests. Once the government accepts a lot of bearings, they

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are stored until requisitioned by an activity. There is no shelf life limit on bearing staves; the time in storage depends upon their usage rate. A separate stock number is associated with each stave of differing cross-section size, length, and special design feature. The three groups obtained from stock for this study had been in stock for approximately 2, 5, and 11 years.

Government supply centers normally control the storage of bearing staves. Warehouse storage temperatures can vary from 0°F to 120°F. After bearing staves are requisitioned for an installation, they are transported from the supply center to the requesting activity. The installation procedure requires that the staves be force-fit into a dovetail housing assembly. Hydraulics is preferred over repeated impacts with hammer or similar device because impact devices frequently damage staves by mushrooming their ends.

Sterntube and strut bearings operate most of their lives in clean seawater and are expected to last from 5 to 10 years. The bearings are usually designed to support approximately 40 lb/in.^{2} unit loading (based upon projected bearing area). The temperature of the seawater may range from near freezing to 90°F. The bearings are intended to operate with a full film of seawater between the surface of the staves and the rotating shaft sleeve. However, their hydrodynamic design makes performance highly dependent upon speed to establish this full film. Ship operating conditions dictate whether full film is formed between the bearing and mating sleeve surface; e.g., operation at slow shaft speeds during startups and shutdowns and operation on jacking gear are some of the conditions under which a film of seawater does not separate the surfaces. Insufficient films can cause bearing and shaft materials to wear. The amount of wear depends upon the properties of the contacting materials, the amount of abrasive contaminants present, the roughness of the con-tacting parts, etc. Stresses at the rubber-to-backing interface are much higher during operation without a lubricating film in the bearing. The highest stresses occur at startup and during the final seconds before the shaft is stopped. Criteria for replacement of staves are provided in NAVSHIPS Technical Manual.

The significance of the various adhesion bond tests for brass-backed stave bearings in MIL-B-17901 relative to the life cycle of the staves is discussed below: The bond tests of the unaged specimens provide a comparative baseline for new staves. Unfortunately little is known about the actual bond strength requirements for sterntube and strut bearings. The 40 lb/in. of test strip width requirement

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reflects the capability of the manufacturers when the specification was being developed. The baseline results of tests on staves in Group I to VI show the manufacturers can now produce staves that greatly exceed the present requirements.

The oil immersion adhesion test provides a relative measure of the resistance to oil. Normally sterntube and strut bearings are not exposed to oil but may encounter it during installation and while operating in polluted water.

The seawater immersion test provides a relative measure of the resistance to deterioration of the bond in the medium in which the bearings will spend 5 to 10 years.

The thermal cycling test reflects changes in temperature during storage and operation. Thermal stresses are produced at the interfaces because the materials have different expansion coefficients.

Each test was conducted using both the exposure time presently specified in MIL-B-17901 and a longer period.

Test Results

Tables 3 through 11 present the data for the adhesion bond tests for the nine groups subjected to the nine environmental conditions. All bond or tear strengths are based upon a 1/2-in. nominal test strip width. The data on strips 1, 3, and 5 for each group specimen are the baselines. Test strips 2, 4, and 6 were pull-tested after exposure to the environmental conditions. Tables 3 through 11 list the results before exposure, the mean value for the three test strips before exposure, and the results and means of the adjacent strips after exposure. The tables also rank the groups by the means, show the incremental difference between means in pounds and percent before and after exposure and give the predominant mode of failure. The change in mean bond or tear strength before and after exposure for each group was tested for significance using the standard deviation calculated for the baseline tests. The standard deviations, s, for the baseline tests are presented in Table 2. If the change in mean bond or tear strength equalled or exceeded twice the standard deviation ($\pm$ 2s), a symbol, (S), was placed in the incremental change column of Tables 3 through 11. Table 12 displays the conditions under which significant changes in strength were observed. A ($\pm$2s) about the sample means from a normal distribution contains 95% of the data. Since the sample sizes were so small and the variances not always identified, this approach was used as a trend indicator only.

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TABLE 3 — FORCE REQUIRED TO SEPARATE TEST STRIP FROM STAVE BACKING
BEFORE AND AFTER EXPOSURE TO SEAWATER FOR 3 MONTHS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	39.0	39.5	32.7	37.1	4	A	38.1	37.6	16.1	30.6	5	A	-6.5	-17.5
II	35.0	29.9	29.3	31.4	6	A	26.8	20.0	26.6	26.5	8	A	-4.9	-15.6
III	30.2	32.1	30.3	30.9	7	A	31.8	26.7	24.7	27.7	7	A	-3.2	-10.4
IV	35.8	32.0	32.3	33.4	5	T&A	33.0	34.1	34.2	33.8	4	A	0.4	1.2
V	-	-	-	-	-	-	48.0	51.1	41.8	47.0	2	T	-	-
VI	53.6	54.6	52.2	53.5	1	A	53.9	48.8	48.8	50.5	1	T&A	-3.0	-5.6
VII	44.8	44.3	41.7	43.6	2	T&A	27.2	30.0	28.0	28.4	6	T&A	-15.2	-34.9
VIII	47.2	40.8	42.3	43.4	3	T	45.0	49.9	45.5	46.8	3	T	3.4	7.8
IX	-	18.7	18	18.4	8	A	17.9	19.2	18	18.4	9	A	0	0

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber. T&A means failure occurred by both tearing and adhesive modes.

TABLE 4 — RESULTS OF BOND TESTS BEFORE AND AFTER BEING
EXPOSED TO SEAWATER FOR 6 MONTHS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	28.9	38.4	39.0	35.4	6	A	37.0	36.6	34.8	36.1	4	A	0.7	2.0
II	25.3	25.8	27.4	26.2	8	T&A	22.9	24.2	26.7	24.6	9	A	-1.6	-6.1
III	24.7	25.9	26.3	25.6	9	A	30.6	29.5	28.0	29.4	7	A	3.8	14.8
IV	28.7	29.7	33.0	30.5	7	A	33.0	34.8	30.7	32.8	5	T	2.3	7.5
V	-	50.0	50.9	50.5	3	T	42.9	42.6	39.2	41.4	3	T	-9.1	-18.0
VI	55.8	43.6	51.6	50.3	2	A	59.1	50.4	55.9	55.1	1	T	4.8	9.5
VII	60.8	56.0	51.7	56.2	1	T	31.8	25.3	22.2	26.4	8	T	-29.8	-53.0(S)
VIII	44.0	42.8	45.8	44.2	4	T	43.7	38.0	52.0	44.6	2	T	0.4	0.9
IX	32.7	39.8	34.1	35.5	5	A	34.3	31.7	31.7	32.6	6	T	-2.9	-8.2

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

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TABLE 5 – RESULTS OF BOND TESTS BEFORE AND AFTER BEING
EXPOSED TO SEAWATER FOR 12 MONTHS

Stave Group	Force Before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	–	50.7	48.9	49.8	1	A	38.4	41.9	32.5	37.6	4	T&A	-12.2	24
II	35.6	26.3	34.4	32.1	7	T	30.9	36.6	31.3	32.9	6	T	.8	2.5
III	32.7	34.5	34.3	33.8	6	T	35.7	33.5	30.7	33.3	5	T	-.5	1.5
IV	28.5	29.2	29.3	29.0	8	A	30.3	30.5	32.7	31.2	7	T&A	2.2	7.6
V	48.4	40.8	42.9	44.0	4	T&A	44.2	41.9	45.9	44	3	T	0	0
VI	52.0	52.4	44.8	49.7	2	A	53.1	47.9	50.3	50.4	2	T&A	.7	1
VII	49.0	47.4	46.9	47.8	3	A	26.2	30.9	35.5	30.9	8	T&A	-16.9	-35(S)
VIII	42.4	40.7	42.4	41.8	5	T	53.6	52.5	50.5	52.2	1	T	10.4	25(S)
IX	19.1	20.2	19.9	19.7	9	A	12.9	13.3	14.5	13.6	9	A	-6.1	31

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber. T&A means that failure occurred by both tearing and adhesive modes.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 6 – RESULTS OF BOND TESTS BEFORE AND AFTER BEING
EXPOSED TO THERMAL CYCLING FOR 45 DAYS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	19.3	39.8	33.6	30.9	6	A	40.1	39.3	22.6	34.0	4	T&A	3.1	10.0
II	35.4	35.0	33.7	34.7	5	T	32.2	32.2	27.9	30.8	6	T	-3.9	-11.2
III	25.0	26.6	26.1	25.9	8	A	27.3	26.7	27.4	27.1	8	A	1.2	4.6
IV	27.6	31.7	30.6	30.0	7	A	35.9	33.8	31.2	33.6	5	T	3.6	12.0
V	37.0	37.8	39.0	37.9	4	A	39.2	44.2	42.0	41.8	3	T	3.9	10.3
VI	50.8	48.2	54.2	51.1	2	A	61.9	56.0	62.2	60.0	1	T&A	8.9	17.4
VII	59.1	52.9	46.7	52.9	1	T	28.5	32.7	31.3	30.8	6	T	-22.1	-41.8(S)
VIII	43.7	39.9	33.1	38.9	3	T&A	37.8	45.1	42.9	41.9	2	T	3.0	7.7
IX	19.7	20.6	20.9	20.4	9	A	21.8	20.1	16.7	19.5	9	A	-0.9	-4.4

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber. T&A means that failure occurred by both tearing and adhesive modes.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 7 – RESULTS OF BOND TESTS BEFORE AND AFTER BEING
EXPOSED TO THERMAL CYCLING FOR 90 DAYS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	28.0	32.4	33.3	31.2	7	A	44.3	45.6	39.3	43.1	6	A	11.9	38.1
II	33.2	29.0	33.6	31.9	6	T&A	39.2	40.4	45.6	41.7	7	T	9.8	30.7(S)
III	25.1	26.9	26.7	26.2	8	A	38.9	36.2	33.7	36.3	8	A	10.1	38.5(S)
IV	31.4	31.3	35.1	32.6	5	T	48.6	45.5	40.1	44.7	4	T	12.1	37.1(S)
V	38.2	42.4	38.7	39.8	4	T&A	51.8	54.6	56.1	54.2	3	T	14.4	36.2
VI	60.7	56.7	59.0	58.8	1	T&A	79.1	72.2	72.0	74.4	1	A	15.6	26.5(S)
VII	52.4	52.4	51.3	52.0	2	T	43.5	43.6	43.7	43.6	5	T	-8.4	-16.2
VIII	42.3	41.8	37.0	40.4	3	T&A	54.1	54.8	54.6	54.5	2	T	14.1	34.9(S)
IX	30.8	23.5	24.0	26.1	9	A	27.6	30.0	36.5	31.4	9	A	5.3	20.3

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 8 – RESULTS OF BOND TESTS BEFORE AND AFTER
EXPOSURE TO OIL FOR 46 HOURS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	45.4	43.8	44.4	44.4	3	T	67.4	64.4	58.4	63.4	2	T	19.0	42.8(S)
II	25.7	28.7	28.1	27.5	8	T&A	37.2	38.5	34.6	36.8	9	A	9.3	33.8(S)
III	24.3	24.0	23.7	24.0	9	A	39.6	37.1	40.2	39.0	7	A	15.0	62.5(S)
IV	30.9	29.5	26.8	29.1	6	T	50.0	52.2	48.8	50.3	4	T&A	21.2	73(S)
V	31.1	27.0	26.7	28.3	7	A	47.0	48.7	49.3	48.3	5	A	20	70.7(S)
VI	63.5	59.8	58.8	60.7	1	T&A	67.7	74.8	74.8	72.4	1	A	11.7	19.3(S)
VII	60.2	40.8	52.5	51.2	2	T	45.6	45.8	47.9	46.4	6	T	-4.8	-9.4
VIII	34.8	36.2	40.9	37.3	4	T	51.0	50.7	55.2	52.3	3	T	15	40.2(S)
IX	29.2	43.9	35.1	36.1	5	A	40.8	37.3	37.3	38.5	8	A	2.4	6.6

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber. T&A means that failure occurred by both tearing and adhesive modes.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 9 - RESULTS OF BOND TESTS BEFORE AND AFTER BEING EXPOSED TO OIL FOR 3 MONTHS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	22.9	35.5	35.1	31.2	7	A	33.5	35.1	32.0	33.5	7	T	2.3	7.4
II	26.2	30.8	31.1	29.4	8	T&A	30.4	31.2	29.9	30.5	8	T	1.1	3.7
III	26.3	31.9	36.1	31.4	6	T&A	40.8	42.2	38.1	40.4	3	T	9.0	28.7(s)
IV	34.5	35.8	35.4	35.2	4	A	35.6	37.5	31.2	34.8	5	T	-0.4	-1.1
V	28.8	28.1	26.9	27.9	9	A	35	32.7	35	34.2	6	T	6.3	22.6
VI	53.9	56.9	56.0	55.6	1	A	57.7	57.9	56.4	57.3	1	A	1.7	3.1
VII	47.3	41.5	41.9	43.6	2	T	37.2	22.2	20.1	26.5	9	T	-17.1	-39.2(s)
VIII	44.9	40.7	41.3	42.3	3	T	40.2	42.2	48.2	43.5	2	T	1.2	2.8
IX	29.3	34.7	37.3	33.8	5	T&A	37.0	35.0	33.9	35.3	4	T	1.5	4.4

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 10 - RESULTS OF BOND TESTS BEFORE AND AFTER BEING EXPOSED TO 158°F FOR 96 HOURS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change***	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	37.9	45.2	48.2	43.8	4	T	46.7	52.2	41.5	46.8	2	T	3.0	6.8
II	37.0	31.1	29.4	32.5	7	T	29.6	32.0	26.8	29.5	7	A	-.3	-9.2
III	26.1	25.2	26.2	25.8	9	A	25.8	29.3	22.0	25.7	9	A	-.1	-.4
IV	48.2	39.8	46.5	44.8	3	T	36.7	33.2	31.8	33.9	6	T	-10.9	-24.3(s)
V	37.2	36.1	36.3	36.5	6	T	40.7	34.9	38.8	38.1	5	T	1.6	4.4
VI	47.0	59.2	42.8	49.7	1	A	57.1	55.9	57.1	56.7	1	T&A	7	14.1
VII	42.6	41.3	42.4	42.1	5	T	38.0	39.4	39.4	38.9	4	T	-3.2	-7.6
VIII	50.5	44.5	45.0	46.7	2	T	41.7	44.6	43.1	43.1	3	T	-3.6	-7.7
IX	25.2	25.0	27.8	26.0	8	A	25.8	29.4	29.2	28.1	8	A	2.1	8.1

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber. T&A means that failure occurred by both tearing and adhesive modes.
***(S) means significant change in mean at 95% confidence level as compared with baseline value.

TABLE 11 – RESULTS OF BOND TESTS BEFORE AND AFTER BEING
EXPOSED TO 158°F FOR 240 HOURS

Stave Group	Force before Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Force after Exposure (lb)*				Ranking of Mean Value	Mode of Failure**	Incremental Change	
	Strip 1	Strip 3	Strip 5	Mean			Strip 2	Strip 4	Strip 6	Mean			avg (lb)	%
I	49.3	48.7	47.7	48.6	2	T	39.8	42.6	39.3	40.6	3	T	-8.0	-16.5
II	25.9	30.4	26	27.4	7	A	31.9	31.2	33.3	32.1	7	T	4.7	17.2
III	27.3	31.5	34.6	31.1	6	T&A	37.0	38.3	37.7	37.7	5	T	6.6	21.2
IV	30.4	35.9	31.6	32.6	4	A	34.6	37.4	31.3	34.4	6	A	1.8	5.5
V	25.9	26.1	26.6	26.2	8	A	40.8	43.0	36.0	39.9	4	A	13.7	52.3
VI	53.9	58.9	56	56.3	1	T	58.0	58.3	56.8	57.7	1	A	1.4	2.5
VII	31.3	33.6	30.2	31.7	5	T	29.5	31.9	33	31.5	8	T	-0.2	-0.6
VIII	47.5	44.1	45.4	45.7	3	T	48.9	45.5	45.0	46.5	2	T	0.8	1.8
IX	22.9	21.6	25.1	23.2	9	A	24.2	21.9	23.1	23.1	9	A	-0.1	-0.4

*All values are based on 1/2-in. nominal test strip width.
**A is failure at adhesive bond; T is failure by tearing of rubber.

TABLE 12 – SIGNIFICANT CHANGES IN STRENGTH OBSERVED*

Stave Group	Environmental Condition								
	Seawater Exposure			Thermal Cycling		Oil Immersion	Oven Aging		
	3 month	6 month	12 month	45 days	90 days	46 hours	3 months	96 hours	240 hours
I						S(+)			
II					S(+)	S(+)			
III					S(+)	S(+)	S(+)	S(-)	
IV					S(+)	S(+)			
V						S(+)			
VI					S(+)	S(+)			
VII		S(-)	S(-)	S(-)	S(+)	S(+)	S(-)		
VIII		S(+)	S(+)		S(+)		S(-)		
IX									

*S(+) and S(-) indicate significant increase and decrease in strength, respectively.

Several specimens from Groups III and IV, which were manufactured by Company B, exhibited spotty areas where there appeared to be no bond established between the rubber and the brass backing. The spotty appearance is shown in Figure 11. The measured bond or tear strength on the test strips exceeded the specification levels.

Exposure to Seawater. Examination of Tables 3, 4, and 5 reveals one striking effect that is illustrated in Figure 12. The bond or tear strength for Group VII (plastic backing) was reduced substantially after 3-, 6-, or 12-months exposure; the differences for 6- and 12-months exposure were statistically significant. The bond or tear strength in Group VIII (rubber backing) increased significantly after 12-months exposure to seawater. The bond or tear strengths for the seven other groups oscillated about the original unaged baseline value after seawater exposure for the three time periods considered. Table 3 shows that after 3-months exposure the mean bond or tear strength tended to decrease for five of the nine groups, increase for two, and remain the same for one. (No data were obtained for the baseline of Group V.) After 6 months the mean bond or tear strength appeared to decrease for four groups and increase for five. After 12 months, the mean bond or tear strength appeared to decrease for four groups, increase for four, and remain unchanged for one. Rankings for Group VII dropped from initial baseline ranking among the top three to sixth or eighth after seawater immersion. The predominant failure mode for Groups VII and VIII was by a combination of tearing and adhesion and by tearing, respectively, after the seawater exposure.

Exposure to Thermal Cycling. Table 6 reveals that after thermal cycling for 45 days, the bond or tear strength in only one group (Group VII) differed significantly from the baseline values. The strength of the bond or tear strength of the rubber after thermal cycling for 45 days for Group VII decreased by about 42%. While two other groups, Group II and IX, showed decreases in mean bond or tear strength and all others showed moderate increases, the changes were not significant.

After thermal cycling for 90 days the group mean bond or tear strength increased in magnitude for eight groups while dropping for only one (see Table 7). Five groups (II, III, IV, VI, and VIII) showed increases exceeding 2s. The only group whose bond values appeared to decrease was Group VII.

After thermal cycling the ranking of Group VII dropped several places, reflecting drops in bond or tear strength in relation to the other eight groups.
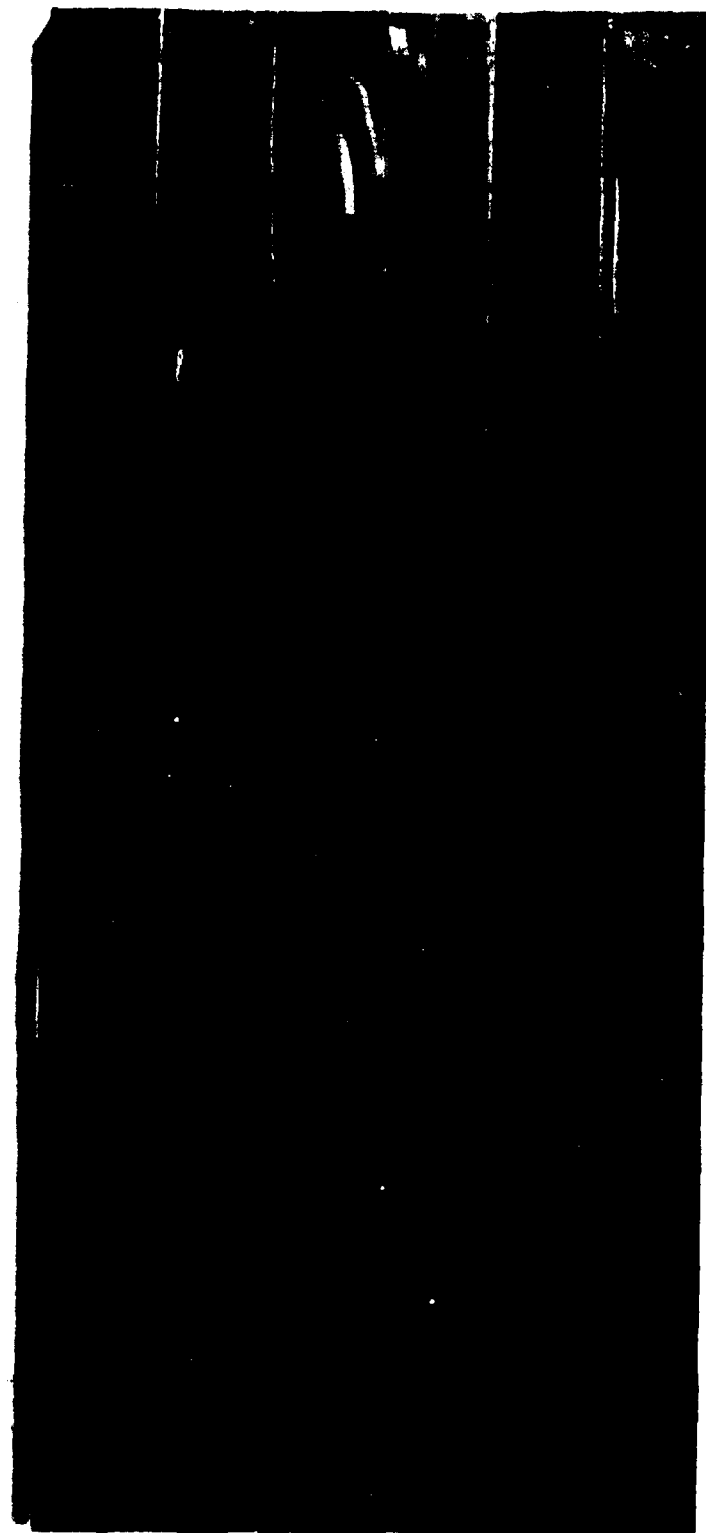
31

Figure 11 - Surface of Specimen After Testing Showing Areas of
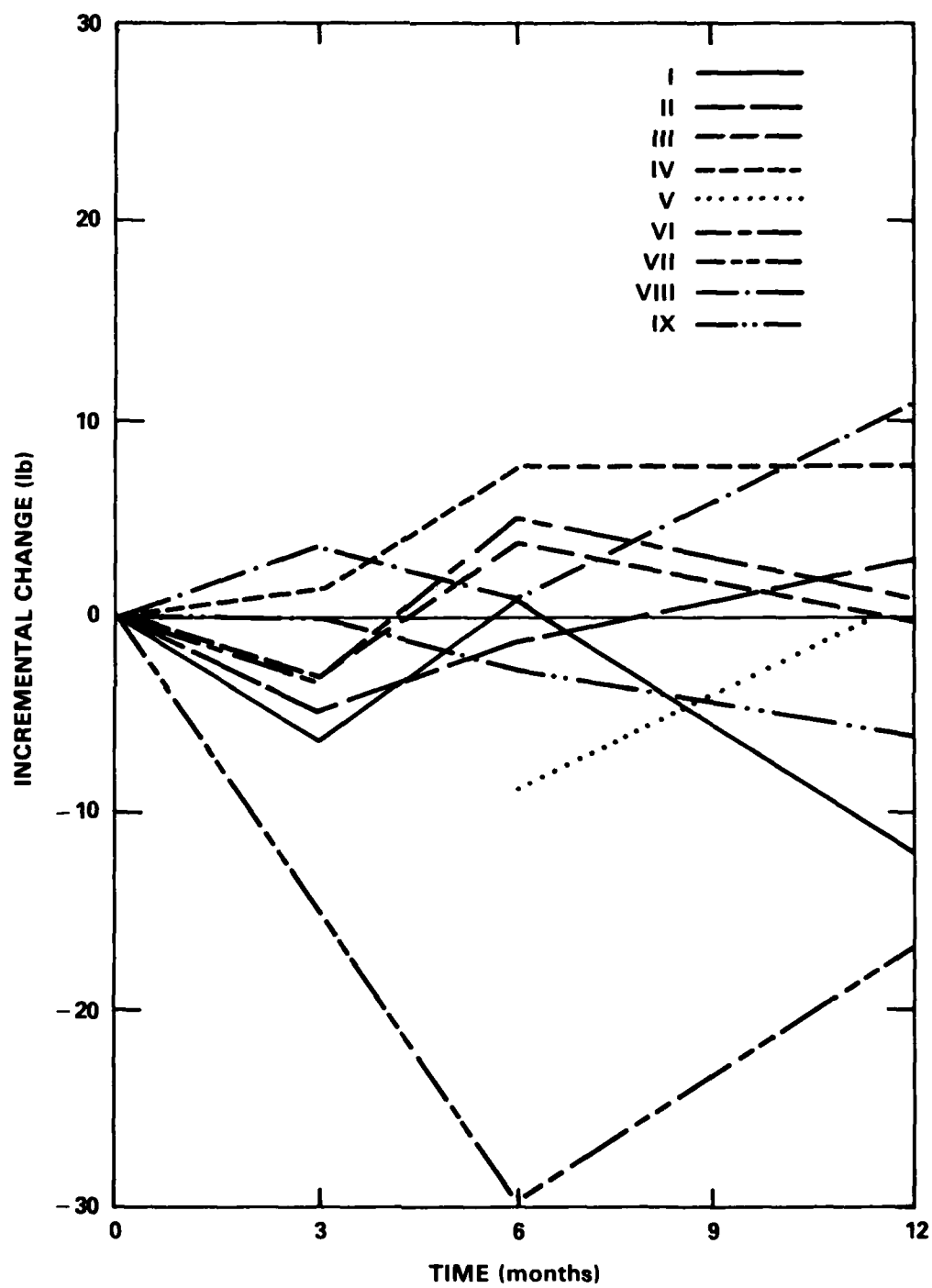No Apparent Bond

Figure 12 — Incremental Bond Strength as Function of Time Immersed in Seawater

Exposure to Oil Immersion. Tables 8 and 9 reveal the following: after immersion in oil for 46 hr, the mean bond or tear strength increased for eight of the nine groups. In seven of the groups the increases are considered statistically significant. Only in Group VII did the mean strength decrease, although not significantly. As a result, the ranking of Group VII changed from 2 before test to 6 after oil immersion for 46 hr.

Immersion in oil for an extended period (3 months) affected only two groups. Strength of Group III increased significantly, resulting in a change in ranking from 6 to 3 before and after exposure. Strength in Group VII decreased significantly, changing this group's ranking from 2 to 9.

Exposure to Oven Aging. Tables 10 and 11 reveal the following: Exposure to 158°F for 96 hr appeared to increase the mean bond or tear strength for four groups and decreased it for five. However, the changes were significant for only one group, Group IV. Group IV ranking shifted from 3 before exposure to 6 after exposure.

Exposure to 158°F for 240 hr appeared to increase the strength for six groups but decreased it for three. None of the changes was significant. Group V increased its mean strength such that its ranking was changed from 8 before to 4 after exposure. Group VII strength decreased, resulting in a ranking change of 5 to 8.

We found no relationship between the magnitude of the bond or tear strength and the mode of failure. For example, Group VI consistently exhibited the highest strength while Groups III and IX were among the lowest. All three groups failed predominantly by adhesive mode. On the other hand Group VIII, which ranked among the best, failed predominantly by rubber tear. The largest changes in ranking were observed for Group VII. It failed predominantly by rubber tear. Groups I, II, IV, and V failed by adhesive, tearing, and combined tearing and adhesive modes.

EVALUATION OF ALTERNATIVE BACKING MATERIALS

We examined the nonmetal backed stave bearings—a hard rubber-backed design and a plastic-backed design. While the hard rubber-backed samples behaved similarly to the conventional brass-backed designs, the plastic-backed stave samples, despite reasonably high as-received bond or tear strength, degraded in strength to a level outside the range for the conventional brass-backed staves in the oil immersion, thermal cycling, and seawater immersion tests. One significant physical difference

with the plastic-backed stave design studied is the use of a soft rubber composition on the surface. The predominant mode of failure for the plastic-backed and the hard-rubber backed staves was by tearing.

While tearing in the rubber is not a measure of the bond strength between the rubber surface and the backing material, the sample fails the adhesive test when the tear strength is less than the specified adhesive strength. Thus the tests of the plastic-backed staves measured the characteristics of the softer rubber composition, not the adhesion strength between the plastic and rubber surfaces. Both hard-rubber and plastic-backed stave bearings exhibit satisfactory characteristics to meet adhesive specification criteria.

PROPOSED SPECIFICATION CRITERIA

There appears to be little data to establish the true bond requirements of the sterntube and strut bearing. There is also a concern about existing specification values used for the adhesion tests. The specification limits the adhesion bond to 40, 30, 30, 30, and 20 lb pull per in. of width respectively, for unaged, seawater immersion, thermal cycling, oven aged, and oil immersion tests. However, the specification of minimum limits does not control the effects of the different environmental parameters. The specification values for tests should be based on baseline values. For example, let the original bond strength be represented by strengths of staves that we tested—for example, 80 lb based upon 1-in. strip width. Suppose that this stave was tested in seawater in accordance with specification procedures and the bond strength dropped to 42 lb; it would be an acceptable stave according to present specification. Continued use in seawater, however, might produce much larger strength reductions and potential bond problems. If the test limits were related to the original level, the effect of that environmental treatment could be assessed directly. Allowing a percent (relative) change from baseline levels seems appropriate; it provides a control for the effect of each aging parameter.

A new set of specification criteria now can be established. They can be based upon the changes observed after exposure to the environmental (aging) tests relative to the baseline adhesion values. The following criteria are proffered and presented in terms of aged versus unaged samples:

- The unaged tear or adhesive bond strength of each test strip must exceed 40 lb/in. of width.

- The tear or adhesive bond strength of all test strips must not be less than 80% of the average bond strength of the unaged samples after seawater immersion for 45 days.

- The tear or adhesive bond strength of all test strips must not be less than 80% of the average bond strength of the unaged samples after thermal cycling for 45 days.

- The tear or adhesive bond strength of all test strips must not be less than 80% of the average bond strength of the unaged samples after oven aging for 96 hr.

- The tear or adhesive bond strength must not be less than 90% of the average bond strength of the unaged samples after oil immersion for 46 hr.

- Adhesion bonds of nonmetal- and metal-backed staves shall be judged by the same criteria.

SUMMARY OF RESULTS

- The mean bond or tear strength in the as-received condition of the nine groups tested varied by a factor of two.

- The mean bond or tear strength of the unaged (as-received) specimens of plastic- and rubber-backed staves ranked second and third respectively of the nine groups. Separation for both groups was primarily by rubber tear.

- Four of the nine groups of staves in the as-received condition failed by adhesion, three failed by a combination of tearing and adhesion, and two failed predominantly by tearing.

- Only Groups I and VIII exhibited a significant difference at the 95% confidence level between bond or tear strength along the edge and in the center strips.

- Exposure of stave specimens to flowing seawater markedly reduced bond or tear strength for the plastic-backed staves (Group VII). The mean bond or tear strength of samples dropped by 35, 53, and 35% after exposure for 3, 6, and 12 months, respectively. Reductions observed have, however, been attributed to loss in tear strength of rubber and not bond deterioration.

- Only one group exhibited significant change in bond or tear strength after exposure to thermal cycling for 45 days. Mean strength of the plastic-backed staves (Group VII) decreased by 42% compared to baseline levels.

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- Significant changes were produced in five of the nine groups after exposure to thermal cycling for 90 days. In all groups but Group VII mean strength increased after exposure to the thermal cycling. The decrease in Group VII was not considered significant.

- Immersion in oil for 46 hr changed the mean sample bond or tear strength in all but one of the groups. In seven groups the increases were considered significant. Only group VII showed decreased strength after exposure.

- Immersion in oil for 3 months produced significant changes in bond or tear strength in two groups; strength of Group III increased and that of Group VII decreased.

- Exposure to 158°F for 96 hr produced significant changes in bond or tear strength of Group IV.

- Exposure to 158°F for 250 hr resulted in no significant changes in mean strength of any group.

- For two manufacturers the mean bond or tear strength of the sample obtained directly from the manufacturer was compared with that of a sample from Federal stock. The strengths differed significantly.

- Of the brass-backed stave bearings tested, less than 2-1/2% would be expected to fail adhesion bond tests in the as-received condition.

- The rubber-backed stave design exhibited tear or adhesion strength behavior similar to that of the conventional brass-backed designs.

- The behavior of the plastic-backed staves (Group VII) differed significantly from that of conventional brass-backed staves in the seawater exposure, thermal cycling, and oil immersion tests. The rubber used in Group VII deteriorated under these environmental conditions.

- Both hard-rubber and plastic-backed stave bearings exhibit satisfactory characteristics to meet adhesive strength specification criteria.

CONCLUSIONS

- Use of 1/2- rather than 1-in.-wide test strips to conduct adhesion bond strength tests of rubber to backing in stave bearings has been demonstrated; it is feasible and valid.

- Use 1/2-in. test strips along the edges of a stave specimen and in the central section to evaluate the bond across the stave.

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RECOMMENDED SPECIFICATION CHANGES

The Military Specification, MIL-B-17901, entitled "Bearing Components, Bonded Synthetic Rubber, Water Lubricated," has been in the process of revision while these adhesion bond tests were being conducted. Naval Sea Systems Command (Code 56X4) is responsible for the specification. Primary changes to the specification involve clarification of procedures for qualification and quality conformance inspection and the addition of class III bearings. Class III are nonmetal-backed stave bearings. The principal benefit of nonmetal-backed stave design is elimination of corrosion of the brass backing material used in Class I. This Center has contributed to the specification revision. Some of the recommendations concerning adhesive bond strength and the rationale behind each are presented below:

Recommended Change - Use 1/2-in.-wide adhesion test strips along each edge and the center of Class I and III bearings.

Rationale: In the middle 1970's bond failures appeared to start at the edges of the staves. The previous qualification procedures required that the adhesion bond strength only over a 1-in.-wide test strip from the center (widthwise) of the stave be tested. No tests were required along the edges. Quality conformance inspection procedures did not require the evaluation of bond strength.

Recommended Change - Specify the tests needed under quality conformance inspection to assure reliable bond strength for all bearings covered by the specification. Examine Class I and III bearings by visual inspection, dimensional inspection, hardness tests, and a bond strength test. A similar requirement shall apply to the Class II design except no adhesion tests will be required. Visual inspection shall consist of inspection of sample staves under a strong light, to determine separations at the interface between the surface rubber face and the backing material. Move a 0.005-in. feeler gage along the bond line to help reveal separations that may not be be visible. Determine the length and depth of separation unbonding by inserting the 0.005-in. feeler gage. Reject the sample if the cumulative length of unbonding is greater than 1 in. or any unbonding of any length allows the feeler gage to be inserted to a depth of 1/4 in. or more. Roughness, holes, cuts, gouges, molding imperfections, or tears in the bearing facing material, all of which would indicate poor workmanship or quality, also shall be cause for rejection. Conduct dimensional inspections on sample bearings to determine compliance with dimensions required by the standard drawing 803-1385664. As a minimum the following dimensions must be

measured and recorded for each sample: (a) Classes I and III - the stave width, thickness, length, side angle, and surface finish of the face material and (b) Class II - the bore, outside diameter, flange dimensions, length, and surface finish of face material.

Rationale: The previous version of MIL-B-17901 required "examination, not involving tests" to determine conformance with requirements of the specification. The interpretation of what was required for the examination was questionable; the specification provided little guidance to assure a high- or acceptable-quality product.

Recommended Change - Require the same bond (or tearing) strength limits and test procedures for class III as is specified for class I.

Rationale: Bearing staves must exhibit the same adhesive bond strengths regardless of backing material.

Recommended Change - Retain the same exposure times for bond strength tests previously specified for oven aged, oil immersed, seawater immersed, and thermally cycled bearings.

Rationale: The amount of time for each aging test was varied under the reported study, but results revealed no benefit from a change to a different length of time.

Recommended Change - Require that all bond strength tests be made on 1/2-in. rather than 1-in. strips.

Rationale: No problems were encountered using 1/2-in. test strips for this report. Use of 1/2-in. widths permits evaluation of bond along both the stave edges and the stave center. All procedures as recommended herein use 1/2-in.-wide test specimens.

Recommended Change - Change aged specification limits to a percent reduction relative to the strengths of the as-received adhesion bond as follows:

As-received - 20 lb/1/2 in. of strip width.

- **Oven aging.** Average bond strength shall not decrease by more than 20% of original specimens.
- **Oil Immersion.** Average bond strength shall not decrease by more than 10% from original specimens.
- **Thermal Cycling.** Average bond strength shall not decrease by more than 20% from original specimens.
- **Seawater Immersion.** Average bond strength shall not decrease by more than 20% from original specimens.

Rationale: Specified limits for the bond tests of the specimens that were environmentally stressed were independent of the original bond strength. Bond strengths of stressed samples were acceptable when they exceeded 40 lb/in. of width. However, the strength could be as low as 20 lb/in. of width after oil immersion tests. The effects of each stressing parameter are to be measured and controlled. Specifying a minimum acceptance limit establishes little control.

Recommended Change - If failure during bond strength tests occurs by tearing in the rubber, the load at which tearing occurs shall be used to judge acceptance or rejection of the bearing stave.

Rationale: Since it is likely that the strength of the adhesive bonding the rubber to the backing may exceed the tear strength of the rubber, the lower value of either failure mode should be used to evaluate the staves and the effects of the various environmental stresses.

FUTURE WORK

Establish actual bond strengths required under service conditions. The acceptance criteria could then be related to such values.

APPENDIX A

SAMPLE CALCULATION TO DETERMINE IF DIFFERENCE AMONG MEAN STRENGTHS OF NINE BEARING GROUPS (UNAGED) IS SIGNIFICANT AT 95 PERCENT CONFIDENCE LEVEL

The following calculation is based on the method of Huntsberger and Billings-ley.[3]

The t test is exact if the universes are normal and the variances are not different. The test gives fairly good results if the universes are moderately non-normal. The sample means and the difference between them are normally distributed.

Sample Calculation – Is there any reason to believe that the mean of as-received samples from Group III is less than that of Group II? Let $\alpha = 0.05$. (Single tail test)

Sample	n	degrees of freedom	$\overline{X}$	$\Sigma (X_i - \overline{X})^2$
III	30	29	28.18	380.03
II	30	29	30.36	353.22
		58		733.25

$$s^2 = \text{pooled estimate of variance} = \frac{\text{pooled sum of squares}}{\text{pooled degrees of freedom}} = \frac{733.25}{58} = 12.64$$

s_d^2 = estimated variance of difference between means

$$s_d^2 = s^2 \left(\frac{1}{n_{II}} + \frac{1}{n_{III}} \right) = 12.64 \left(\frac{1}{30} + \frac{1}{30} \right) = 0.84$$

$$s_d = 0.92$$

The hypothesis is $H_o : \mu_{II} = \mu_{III}$. The alternative hypothesis is $H_a : \mu_{II} > \mu_{III}$;

$$t = \frac{\overline{X}_{II} - \overline{X}_{III}}{s_d} = \frac{30.36 - 28.18}{.92} = 2.37$$

The critical region is $t > t_{.05,58} \approx 1.671$. The calculated t is greater than the tabular value; therefore, we reject the hypothesis and conclude that $\mu_{II} > \mu_{III}$.

APPENDIX B

SAMPLE CALCULATION TO DETERMINE IF DIFFERENCE BETWEEN MEAN
STRENGTHS OF END AND CENTER TEST STRIPS (UNAGED) IS
SIGNIFICANT AT 95 PERCENT CONFIDENCE LEVEL

The following calculation is based upon the method of Huntsberger and
Billingsley.[3]

The t test is exact if the universes are normal and the variances are not dif-
ferent. The test gives fairly good results if the universes are moderately non-
normal. The sample means and the difference between them are normally distributed.

Sample Calculations – For Group I, is there any reason to believe that the mean
bond value of the end test strip is less than that of the center test strips? Let
$\alpha = 0.05$ (single tail test).

We test the hypothesis $H_o : \mu_{end} = \mu_{center}$ against the alternative
$H_a : \mu_{end} < \mu_{center}$.

Sample	n	degrees of freedom	$\overline{X}$	$\Sigma(X_i - \overline{X})^2$
end	9	8	34.36	824.18
center	20	19	41.12	700.05
		27		1524.23

s^2 = pooled estimate of variance = $\dfrac{\text{pooled sum of squares}}{\text{pooled degrees of freedom}} = \dfrac{1524}{27} = 56.45$

s_d^2 = estimated variance of difference between means

$s_d^2 = s^2 \left(\dfrac{1}{n_{end}} + \dfrac{1}{n_{center}} \right) = 56.45 \left(\dfrac{1}{9} + \dfrac{1}{29} \right) = 9.09$

$s_d = 3.02$

$t = \dfrac{\overline{X}_{center} - \overline{X}_{end}}{s_d} = 2.24$

The critical region for $\alpha = 0.05$ is $t > t_{0.05,27} = 1.703$. Since the calculated t
is greater than the tabular t value, the hypothesis $\mu_{end} = \mu_{center}$ is rejected. It
is concluded that $\mu_{end} < \mu_{center}$.

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REFERENCES

1. Military Specification, MIL-B-17901A, "Bearing Components, Bonded Synthetic Rubber, Water Lubricated." (Revision B, which reflected much of this work, was issued 17 June 1983).

2. Standard Drawing, Naval Ship Systems Command Drawing 803-1385664.

3. Huntsberger, D. V. and P. Billingsley, "Elements of Statistical Inference," 4th. ed., Allyn and Bacon, Inc., Boston (1977) pp. 219-227.

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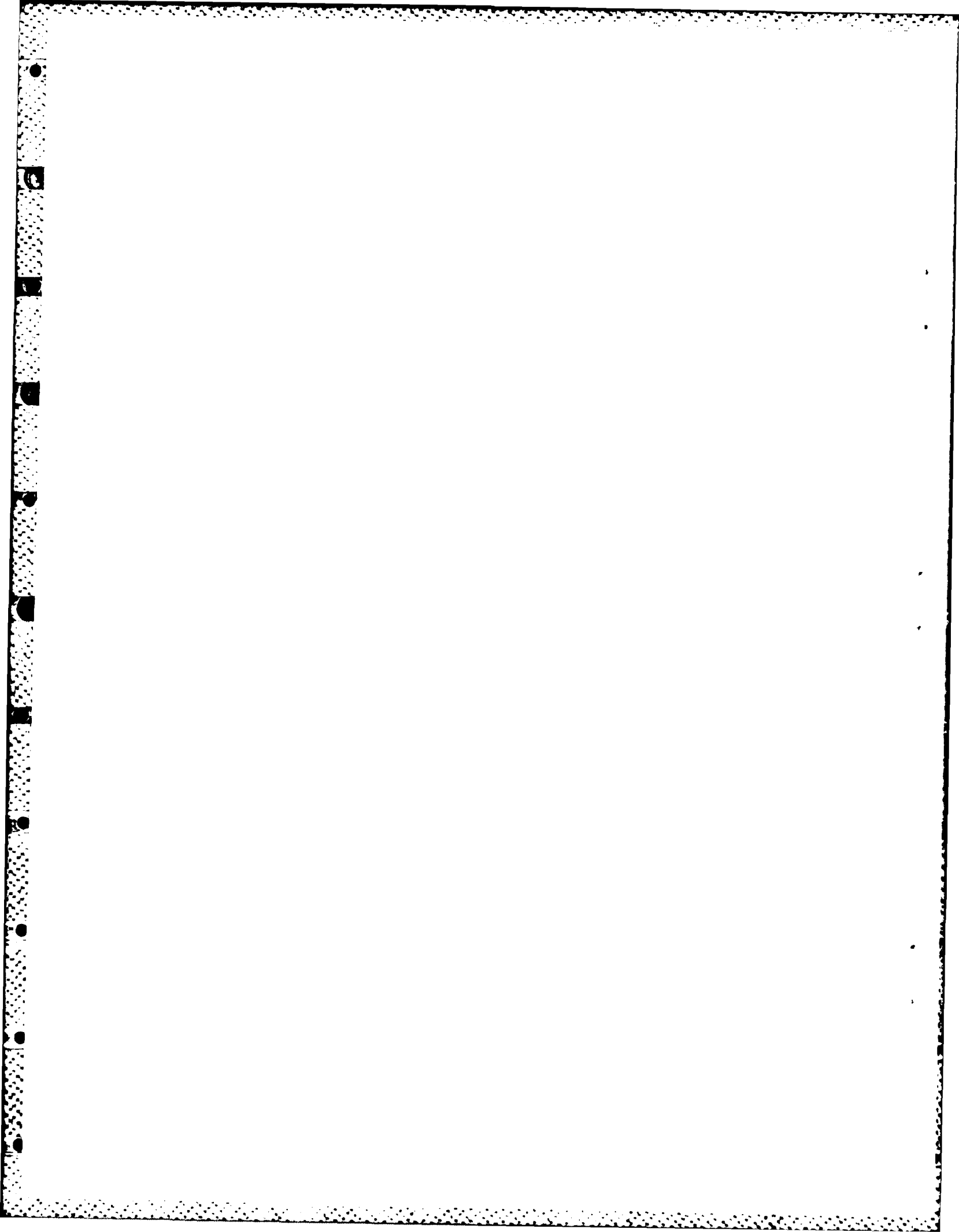
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